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# Molecular Structure of Copper and $\mu$ -Oxodiiron Octafluorocorrole Derivatives: Insights into Ligand Noninnocence

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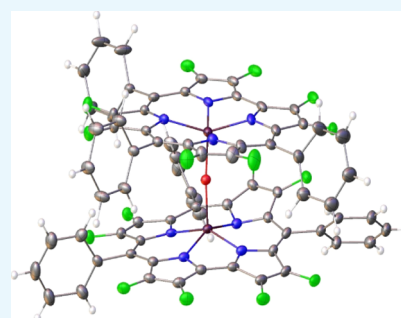


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**ABSTRACT:** Single-crystal X-ray structures were obtained for the copper and  $\mu$ -oxodiiron complexes of 2,3,7,8,12,13,17,18-octafluoro-5,10,15-triphenylcorrole, hereafter denoted as  $\text{Cu}[\text{F}_8\text{TPC}]$  and  $\{\text{Fe}[\text{F}_8\text{TPC}]\}_2\text{O}$ . A comparison with the crystal structures of other undecasubstituted Cu corroles, including those with H, Ar, Br, I, and  $\text{CF}_3$  as  $\beta$ -substituents, showed that the degree of saddling increases in the order:  $\text{H} \lesssim \text{F} < \text{Ar} \lesssim \text{Br} \lesssim \text{I} < \text{CF}_3$ . In other words,  $\text{Cu}[\text{F}_8\text{TPC}]$  is marginally more saddled than  $\beta$ -unsubstituted Cu triarylcorroles, but substantially less saddled than Cu undecaarylcorroles,  $\beta$ -octabromo-*meso*-triarylcorroles, and  $\beta$ -octaiodo-*meso*-triarylcorroles, and far less saddled than Cu  $\beta$ -octakis(trifluoromethyl)-*meso*-triarylcorroles. As for  $\{\text{Fe}[\text{F}_8\text{TPC}]\}_2\text{O}$ , the moderate quality of the structure did not allow us to draw firm conclusions in regard to bond length alternations in the corrole skeleton and hence also the question of ligand noninnocence. The Fe–O bond distances, 1.712(8) and 1.724(8), however, are essentially identical to those observed for  $\{\text{Fe}[\text{TPFPC}]\}_2\text{O}$ , where  $\text{TPFPC}^{3-}$  is the trianion of 5,10,15-tris(pentafluorophenyl)corrole, suggesting that a partially noninnocent electronic structural description may be applicable for both compounds.



## INTRODUCTION

Well over a half-century ago, the Danish chemist C. K. Jørgensen distinguished ligands as “innocent” and “suspect,” a suspect—or “noninnocent,” to use the modern term—ligand being one that leaves the oxidation state of the central metal uncertain or debatable.<sup>1</sup> In a typical situation, an electron or a hole cannot be approximated as belonging to either the metal or the ligand, but must be regarded as delocalized over the two.<sup>2,3</sup> Noninnocent ligands thus pose major challenges for inorganic spectroscopists and theoreticians.<sup>4</sup> Such ligands are also of considerable practical importance: by acting as reservoirs of electrons or holes, noninnocent ligands facilitate a variety of reactions that innocent ligands do not.<sup>5</sup> First-row transition metal corroles, as it happens, afford some of the best-characterized examples of noninnocent ligands.<sup>6–9</sup>

A variety of tools, spectroscopic and otherwise, have been used to characterize ligand noninnocence. Of these, NMR and EPR<sup>10</sup> spectroscopy are arguably the most direct because under favorable circumstances they provide a direct probe of the unpaired electron density. Paramagnetic FeCl and Fe-aryl corroles provide some of the most elegant examples of the use of <sup>1</sup>H NMR spectroscopy to elucidate the spin density distributions of noninnocent systems.<sup>11–17</sup> These methods, however, are useless for a considerable number of systems in which intramolecular spin couplings result in a diamagnetic ground state. Key examples of such cryptically noninnocent systems include copper,<sup>18–21</sup>  $\mu$ -oxodiiron,<sup>11,22</sup> and iron-nitrosyl<sup>23–25</sup> corroles. For such systems, more indirect means, such as X-ray structure determination and electrochemistry, can be used to glean electronic structure

information. It is against this backdrop that we report single-crystal X-ray structures of the copper and  $\mu$ -oxodiiron complexes of 2,3,7,8,12,13,17,18-octafluoro-5,10,15-triphenylcorrole, hereafter denoted  $\text{Cu}[\text{F}_8\text{TPC}]$  and  $\{\text{Fe}[\text{F}_8\text{TPC}]\}_2\text{O}$ , respectively.

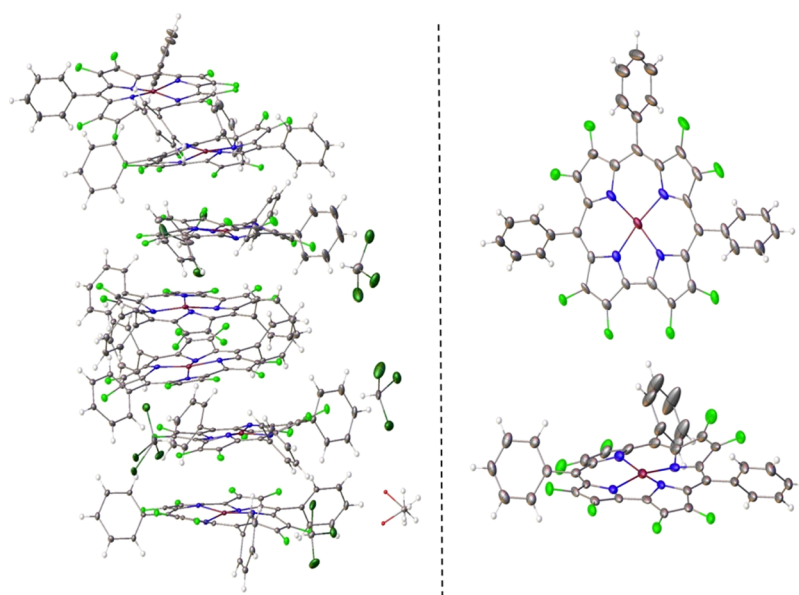
$\beta$ -Octafluorinated porphyrins and corroles are uncommon ligands, primarily because of the relative inaccessibility of 3,4-difluoropyrrole.<sup>14,26,27</sup> However, they are of great interest because their metal complexes are expected to exhibit significantly perturbed reactivity as well as unusual solubility, conductivity, and optical properties. Thus,  $\beta$ -octafluorinated cobalt(III) corroles have been found to be highly active catalysts for water splitting, for both the oxygen<sup>28</sup> and hydrogen evolution reactions.<sup>29</sup> As strongly perturbed analogues of simple corroles,  $\beta$ -octafluorocorroles also afford fascinating subjects for studies of ligand noninnocence.<sup>30</sup> Such studies, however, have been hobbled by an almost<sup>31</sup> complete lack of X-ray crystal structures for  $\beta$ -octafluorocorrole derivatives, a gap in our knowledge that we have finally been able to close via this study.

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**Figure 1.** Thermal ellipsoid plots (at 30% probability) of Cu[F<sub>8</sub>TPC]. Left: the seven Cu corroles in the asymmetric unit, along with solvent molecules (CHCl<sub>3</sub>). Right: Close-up views of one of the Cu[F<sub>8</sub>TPC] molecules.

## RESULTS AND DISCUSSION

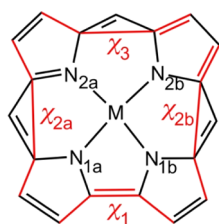
Ligand noninnocence manifests itself in copper corroles via a curious phenomenon that we have called intrinsic saddling.<sup>32</sup> Thus, copper corroles are saddled even in the absence of sterically hindering, peripheral substituents.<sup>32,33</sup> In the currently accepted picture, which is supported by an extensive array of structural, spectroscopic, electrochemical, and quantum chemical studies, saddling is engendered primarily by a Cu( $d_{x^2-y^2}$ )–corrole( $\pi$ ) orbital interaction, which endows the molecules with substantial Cu<sup>II</sup>–corrole<sup>•2-</sup> character.<sup>18–21,32–40</sup> Sterically hindering substituents can accentuate the saddling,<sup>34–40</sup> but substituents alone, in the absence of the specific orbital interaction, do not bring about saddling in metalcorroles (the case of gold corroles being particularly instructive<sup>41–46</sup>). Interestingly, the corrolazine macrocycle, which has an even more contracted N<sub>4</sub> core than corroles and does not adopt noninnocent electronic structures as readily, yields planar, innocent Cu(III) complexes.<sup>47</sup> Likewise, carbacorroles such as azulicorrole also yield planar Cu(III) complexes.<sup>48</sup>

The X-ray structure of Cu[F<sub>8</sub>TPC] (Figure 1, Tables 1 and 2) revealed distinctly saddled Cu–corrole macrocycles. Interestingly, a total of seven unique metalcorrole molecules were found in the asymmetric unit, providing significant insight into the plasticity of the macrocycle vis-à-vis saddling. Indeed, the saddling dihedrals defined and listed in Table 2 were found to vary over several degrees, as expected for a soft coordinate, and as for other Cu corrole derivatives, the following trend was observed:  $\chi_1 < \chi_2 \approx \chi_3$ . A comparison with crystal structures of other undecasubstituted Cu corroles, including those with H,<sup>32,33</sup> Ar,<sup>35,36</sup> Br,<sup>20,34,37</sup> I,<sup>40</sup> and CF<sub>3</sub><sup>39</sup> as  $\beta$ -substituents, proved instructive and showed that the degree of saddling increases in the order H  $\lesssim$  F < Ar  $\lesssim$  Br  $\lesssim$  I < CF<sub>3</sub>, which is essentially the order of their Charton<sup>49</sup> or Sterimol B1<sup>50</sup> steric parameters (Table 3).<sup>51</sup> In other words, Cu[F<sub>8</sub>TPC] is marginally more saddled than  $\beta$ -unsubstituted Cu triarylcorroles, but substantially less saddled than Cu undecaarylcorroles,  $\beta$ -octabromo-*meso*-triarylcorroles, and  $\beta$ -octaiodo-*meso*-triarylcorroles, and far less saddled than Cu  $\beta$ -octakis-

**Table 1.** Crystal and Refinement Data

	Cu[F <sub>8</sub> TPC]	{Fe[F <sub>8</sub> TPC]} <sub>2</sub> O
empirical formula	C <sub>37.86</sub> H <sub>16.14</sub> Cl <sub>2.14</sub> CuF <sub>8</sub> N <sub>4</sub> O <sub>0.14</sub>	C <sub>74</sub> H <sub>30</sub> F <sub>16</sub> Fe <sub>2</sub> N <sub>8</sub> O
formula mass	820.77	1462.76
temperature [K]	100(2)	100(2)
crystal system	monoclinic	monoclinic
space group	P2 <sub>1</sub> /c	Cc
$\lambda$ [Å]	0.7288(1)	0.7288(1)
$a$ [Å]	23.636(2)	20.065(3)
$b$ [Å]	34.020(3)	21.913(3)
$c$ [Å]	30.888(3)	16.255(3)
$\alpha$ [°]	90	90
$\beta$ [°]	102.819(3)	98.773(5)
$\gamma$ [°]	90	90
$Z$	28	4
$V$ [Å <sup>3</sup> ]	24,218(3)	7063.4(19)
density [Mg m <sup>-3</sup> ]	1.576	1.376
crystal size (mm <sup>3</sup> )	0.300 × 0.080 × 0.030	0.120 × 0.020 × 0.020
$\theta$ range [°]	1.183–21.498	2.106–22.654
meas. Reflections	384,508	51,140
unique reflections	25,642	8592
parameters	3358	911
restraints	36	38
$R_{\text{int}}$	0.0881	0.0647
$R_1, wR_2$ ( $I > 2\sigma$ )	0.0779, 0.2073	0.0669, 0.1728
$R_1, wR_2$ (all data)	0.0861, 0.2136	0.0696, 0.1774
$S$ (GooF) all data	1.034	1.082
max/min res. dens. [e Å <sup>-3</sup> ]	1.406/–1.059	0.854/–0.396

(trifluoromethyl)-*meso*-triarylcorroles. It may be worth recalling that even for the exceptionally sterically hindered octakis(trifluoromethyl)-*meso*-triarylcorrole ligands, the Au

**Table 2.** Copper–Nitrogen Distances (Å) and Saddling Dihedrals (°) for the Seven Unique Molecules in the Asymmetric Unit of Cu[F<sub>8</sub>TPC]

Cu[F <sub>8</sub> TPC]	χ <sub>1</sub>	χ <sub>2a</sub>	χ <sub>2b</sub>	χ <sub>3</sub>	Cu–N <sub>1a</sub>	Cu–N <sub>1b</sub>	Cu–N <sub>2a</sub>	Cu–N <sub>2b</sub>
molecule 1	24.0(8)	44.7(1.5)	52.1(1.5)	52.9(1.3)	1.914(7)	1.902(7)	1.907(7)	1.909(7)
molecule 2	23.1(7)	49.0(1.2)	47.9(1.3)	56.1(1.2)	1.908(6)	1.915(7)	1.906(7)	1.904(6)
molecule 3	25.1(8)	49.8(1.5)	54.2(1.3)	62.1(1.4)	1.909(7)	1.907(7)	1.920(7)	1.908(8)
molecule 4	22.6(8)	50.8(1.5)	49.2(1.5)	52.5(1.3)	1.914(7)	1.905(8)	1.931(8)	1.904(7)
molecule 5	20.9(8)	47.7(1.5)	53.0(1.5)	54.9(1.3)	1.903(7)	1.899(7)	1.911(7)	1.903(8)
molecule 6	24.3(8)	49.4(1.6)	47.4(1.5)	48.8(1.4)	1.897(7)	1.910(8)	1.908(8)	1.920(7)
molecule 7	19.6(8)	44.3(1.4)	47.1(1.6)	49.3(1.3)	1.909(7)	1.896(7)	1.903(7)	1.904(7)

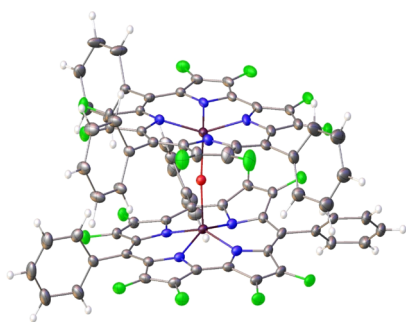
**Table 3.** Copper–Nitrogen Distances (Å) and Saddling Dihedrals (°) for Selected Cu Corroles

complex	Cu–N <sub>1</sub> <sup>a</sup>	Cu–N <sub>2</sub> <sup>a</sup>	χ <sub>1</sub>	χ <sub>2</sub> <sup>a</sup>	χ <sub>3</sub>	refs
Cu[TPC]	1.891	1.891	27.5	53.4	48.7	33
Cu[F <sub>8</sub> TPC]	1.897–1.914	1.896–1.915	19.6–24.3	44.3–54.2	48.8–62.1	this work
Cu[(pCF <sub>3</sub> Ph) <sub>8</sub> TPC]	1.902	1.897	40.9	60.1	66.0	35
Cu[Br <sub>8</sub> TpMePC]	1.916	1.916	44.7	65.9	57.3	20
Cu[I <sub>8</sub> TpCNPC]	1.921	1.922	45.3	67.0	57.3	40
Cu[(CF <sub>3</sub> ) <sub>8</sub> TpFPC]	1.921	1.925	57.2	86.4	84.5	39

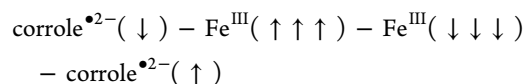
<sup>a</sup>Average of two values for each experimental structure.

complex is rigorously planar because of the energetically mismatched nature of the Au(Sd<sub>x<sup>2</sup>−y<sup>2</sup></sub>)–corrole(π) orbital interaction.<sup>46</sup>

The X-ray structure of {Fe[F<sub>8</sub>TPC]}<sub>2</sub>O clearly revealed a linear Fe–O–Fe unit (Figures 2 and 3), as also observed for

**Figure 2.** Thermal ellipsoid plots (at 30% probability) of {Fe[F<sub>8</sub>TPC]}<sub>2</sub>O.

{Fe[OEC]}<sub>2</sub>O<sup>52</sup> and {Fe[TPFPC]}<sub>2</sub>O,<sup>53</sup> where TPFPC<sup>3−</sup> is the trianion of 5,10,15-tris(pentafluorophenyl)corrole. Our earlier work has suggested that μ-oxodiiron corroles are noninnocent with a significant contribution with the following intramolecularly spin-coupled description<sup>11,22</sup>



One line of evidence in support of this conclusion is that the X-ray structure of {Fe[TPFPC]}<sub>2</sub>O exhibits subtle but characteristic bond length alternations within and adjacent to the

bipyrrole units of macrocycles, which are now recognized as a hallmark of noninnocent metallocorroles. Unfortunately, the moderate quality of the present structure (i.e., the e.s.d.'s in the corrole skeletal distances) does not allow us to draw a firm conclusion on this point. The Fe–O bond distances, 1.712(8) and 1.724(8), however, are essentially identical to those observed for {Fe[TPFPC]}<sub>2</sub>O, which leads us to suggest that a partially noninnocent electronic structure description may also be apt for the present compound.

## CONCLUSION

The X-ray structures of two β-octafluoro-*meso*-triphenylcorrole derivatives have afforded new insight into our growing understanding of the structural manifestations of ligand noninnocence in metallocorrole systems. Thus, Cu[F<sub>8</sub>TPC] was found to be only slightly more saddled than β-unsubstituted Cu triarylcorroles and substantially less so than Cu β-octabromo-*meso*-triarylcorroles, consistent with the van der Waals radii of H, F, and Br. Accordingly, a noninnocent electronic structure, with substantial Cu<sup>II</sup>–corrole<sup>•2−</sup> character, appears plausible for Cu[F<sub>8</sub>TPC]. Unfortunately, the moderate quality of the X-ray structure of {Fe[F<sub>8</sub>TPC]}<sub>2</sub>O did not allow a definitive evaluation of ligand noninnocence based on an examination of the corrole skeletal bond distances. The fact that {Fe[F<sub>8</sub>TPC]}<sub>2</sub>O exhibits a nearly identical geometry for the Fe–O–Fe moiety as {Fe[TPFPC]}<sub>2</sub>O, however, suggests that the two compounds probably share a similar, partially noninnocent electronic structure.

## MATERIALS AND INSTRUMENTATION

All reagents and solvents were generally used as purchased. Ultraviolet–visible (UV–vis) spectra were recorded on an HP





CH<sub>2</sub>Cl<sub>2</sub> as an eluent. The product was obtained as the first reddish-brown band. Yield: 7.0 mg (0.0048 mmol, 40%). Brown needles of X-ray quality were obtained by diffusion of *n*-hexane vapor into a concentrated solution of the compound in CH<sub>2</sub>Cl<sub>2</sub> within 13 d.

UV–vis (CH<sub>2</sub>Cl<sub>2</sub>)  $\lambda_{\text{max}}$  [nm,  $\epsilon \times 10^{-4}$  (M<sup>-1</sup> cm<sup>-1</sup>): 353 (Soret, 14.23). <sup>1</sup>H NMR:  $\delta$  7.62–7.54 (m, 4H), 7.54–7.44 (m, 10H), 7.44–7.37 (m, 8H), 7.25 (d, 4H,  $J$  = 7.40 Hz), 7.20 (t, 2H,  $J$  = 7.56 Hz), 6.71 (d, 2H,  $J$  = 7.32 Hz). <sup>19</sup>F NMR:  $\delta$  –145.49 (s, 4F), –146.21 (d, 4F,  $J$  = 7.22 Hz), –147.80 (d, 4F,  $J$  = 7.41 Hz), –157.84 (s, 4F). MS (negative ion mode, major isotopomer) [M]<sup>–</sup>: 1462.0936 (expt), 1462.0996 (calcd).

**X-ray structure determination.** X-ray data for Cu[F<sub>8</sub>TPC] and {Fe[F<sub>8</sub>TPC]}<sub>2</sub>O were collected on the beamline 12.2.1 at the Advanced Light Source, Lawrence Berkeley National Laboratory. The crystals were mounted on a MiTeGen kapton loop and placed in a 100(2) K nitrogen cold stream provided by the Oxford Cryostream 800 Plus low-temperature apparatus on the goniometer head of a Bruker D8 diffractometer equipped with a PHOTON II CPAD detector operating in shutterless mode. Diffraction data were collected using synchrotron radiation monochromated using silicon (111) to a wavelength of 0.7288(1) Å. A full-sphere of data were collected for each crystal using a combination of phi and omega scans with scan speeds of 1.0 s per 4° for the phi scans and 1 s per degree for the omega scans at 2 $\theta$  = 0 and –20, with different levels of beam attenuation, respectively. Absorption corrections were applied using SADABS.<sup>54</sup> The structures were solved by intrinsic phasing (SHELXT)<sup>55</sup> and refined by full-matrix least squares on  $F^2$  (SHELXL-2014).<sup>56</sup> All nonhydrogen atoms were refined anisotropically. Hydrogen atoms were geometrically calculated and refined as riding atoms. For Cu[F<sub>8</sub>TPC], definable solvent molecules were found in the electron density map as Q peaks and modeled appropriately; the peaks that could not be definitively assigned to either methanol or chloroform were treated with the solvent mask routine included in OLEX2.<sup>57</sup> Additionally, the crystal structure resolution was truncated at 0.99 Å because of resolution shells beyond 0.99 Å having  $R_{\text{int}}$  values greater than 25%. These additional higher resolution reflections have signal-to-noise ratios that are too low to contribute constructively to the structure solution and would have probably required additional restraints. For {Fe[F<sub>8</sub>TPC]}<sub>2</sub>O, the crystal structure resolution was truncated at 0.95 Å for the same reasons as indicated above for Cu[F<sub>8</sub>TPC].

## ■ ASSOCIATED CONTENT

### Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acsomega.0c01035>.

<sup>1</sup>H and <sup>19</sup>F NMR, mass, and UV–vis spectra (PDF)

Crystallographic data (CIF)

Crystallographic data (CIF)

## Accession Codes

The crystal structures reported in this paper have been deposited at the Cambridge Crystallographic Data Centre and assigned the deposition numbers CCDC 1978931 and 1978935.

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### Notes

The authors declare no competing financial interest.

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